WasteBanned: Supporting Zero Waste Fashion Design Through Linked Edits

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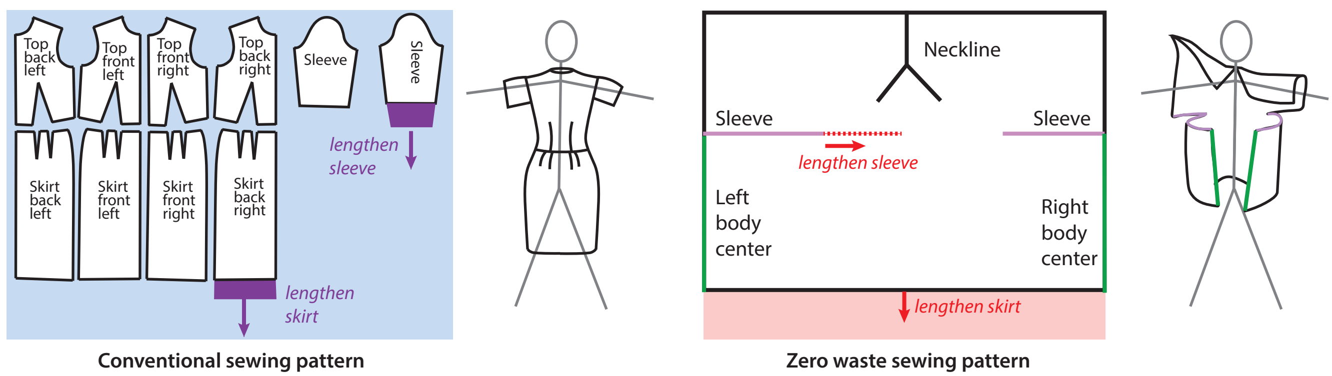

Figure 1: Traditional sewing pattern layouts (left) leave wasted fabric (blue) between the pattern panels (white). Making edits, such as lengthening the skirt or sleeve, is pretty easy because of this extra material. Zero waste sewing layouts (right) use all of the available fabric, resulting in no wasted fabric. However, making a garment zero waste imposes strict constraints, which makes editing difficult. For example, lengthening the skirt requires additional fabric that is not available (red region, right). Lengthening the sleeve (red dashed line, right) affects the fit of the dress because doing so would necessarily reduce the width of the back area. WasteBanned encodes these zero waste editing constraints to facilitate zero waste garment design.

ABSTRACT

The commonly used cut-and-sew garment construction process, in which 2D fabric panels are cut from sheets of fabric and assembled into 3D garments, contributes to widespread textile waste in the fashion industry. There is often a significant divide between the design of the garment and the layout of the panels. One opportunity for bridging this gap is the emerging study and practice of zero waste fashion design, which involves creating clothing designs with maximum layout efficiency. Enforcing the strict constraints of zero waste sewing is challenging, as edits to one region of the garment necessarily affect neighboring panels. Based on our formative work to understand this emerging area within fashion design, we present WasteBanned, a tool that combines CAM and CAD to help users prioritize efficient material usage, work within these zero waste constraints, and edit existing zero waste garment patterns. Our user evaluation indicates that our tool helps fashion designers edit zero waste patterns to fit different bodies and add stylistic variation, while creating highly efficient fabric layouts.

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CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

Fabrication, Zero waste, Design tools, Sustainable design

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1 INTRODUCTION

The rise of fast fashion, made possible by access to cheaper materials and labor, has greatly contributed to an increase in wasted textiles [48]. Most of the clothes we wear are produced through what is called a "cut and sew" process, in which 2D fabric panels are cut from rectangular sheets of fabric and then sewn into 3D garments. The amount of fabric required to produce a garment relies on the size of these panels and how efficiently they are arranged on the fabric. Even with careful layouts, irregularly shaped pattern pieces cannot be arranged in an orderly fashion, and the gaps between panels result in wasted fabric (Fig. 1, left). One of the primary causes of inefficiencies in garment design is the divide between the design and layout (also called *pattern cutting*) processes. The pattern is designed and edited, and then the pattern panels are arranged on sheets of fabric. Fashion designers typically work under the assumption that more fabric can be requested. According to Timo Rissanen, a fashion design educator, "Pattern cutting is usually presented as a rigid technical process" with little opportunity for creative freedom. Relatively few fashion designers receive training in pattern cutting and have awareness of how the designs they choose affect the efficiency of the material usage [55].

One opportunity for bridging this divide between visual design and pattern cutting (i.e., fabric layout) is the emerging study and practice of *zero waste clothing design*, which refers to clothing designs with highly efficient layouts. While zero waste clothing, such as clothing made from a whole animal hide and Japanese kimonos, has existed for thousands of years, zero waste clothing design has become a more formalized area of study for a small community of fashion designers since 2012 [55]. By pushing the limits of material efficiency, zero waste fashion designers have called for making pattern cutting a more creative process and bringing material considerations earlier into the design process. In the zero waste design process, designers aim to use all of the available material, and as a result, have to incorporate both knowledge of the design process as well as an awareness of the layout of the garment.

Designing zero waste garments has been described as a challenging puzzle [54]. Prior work in related puzzles, such as Tetris, shows that reasoning about shape rotations and placements in your head is quite challenging without realizing the rotations in the physical world [28]. Designing a garment to use all or nearly all of the available material heavily constrains the set of designs that will use all available fabric, fit a person properly, and look stylish. Designing any garment from scratch is challenging, but in this case, even editing an existing pattern for size or style changes can be tricky. The challenges of zero waste design include the following:

(1) **Connecting design and material layout**: The fashion designer must worry about both the visual design of the garment and optimizing for layout efficiency at the same time, which is an unusual challenge that is not covered in a typical fashion design curriculum or common sewing processes.
(2) **Adjusting panels for maximally efficient packing**: Sewing pattern panel shapes tend to be irregular, which leads to inefficient packing (and packing itself is known to be a computationally hard problem). Zero waste fashion designers must cleverly adapt these irregular shapes to ones that can fit together with other panels.
(3) **Linked edits**: Design adjustments are inherently linked because of the maximally packed layout; moving the edge of one panel affects the shape of neighboring panels, which can inadvertently alter fit or style (Fig. 1).

Linked edits are the most critical part of zero waste design. In conventional workflows edits to one part of the garment are unlikely to affect neighboring panels because the designer can always just use more fabric or cut more into the leftover areas between panels (Fig. 1, left). In zero waste design, however, edits have to be linked because moving the edge of one sleeve panel, for example, would cut into the neighboring body panel (Fig. 1, right).

Currently the small community of zero waste sewing pattern designers use a wide range of tools and techniques for producing patterns. Some create paper mock ups, while others utilize digital tools, such as Adobe Illustrator or Clo3D [18, 55, 63]. These tools, however, require keeping in mind a large number of design and construction constraints and require extensive trial and error. There are currently no specialized tools for incorporating the strict set of design constraints that zero waste sewing imposes. We introduce WasteBanned, a tool which encodes zero waste sewing constraints and supports the design and simulation of zero waste designs. In our tool we present three different visualization panels: the layout view, the alignment view, and the simulation view. The layout view, in particular, helps put material and fabrication constraints at the forefront of the user's mind, essentially providing CAM (computer aided manufacturing) functionality with a domain-specific CAD (computer aided design) back end. This CAM and CAD functionality is necessitated by the overconstrained nature of zero waste sewing patterns in which changes to one panel must affect neighboring ones. In this paper we contribute the following:

(1) A software tool for designing zero waste sewing patterns that supports CAD and CAM together
(2) A three-view UI that supports design, manufacturing, and fit editing for zero waste garments
(3) A set of constraints that occur in zero waste fashion design

We performed a small user evaluation focused on adapting existing zero waste sewing patterns to fit different bodies and add personalized stylistic elements. Our evaluation indicates that our tool helps users adjust existing zero waste fashion designs to fit and add stylistic variation, while adhering to the zero waste constraints.

2 ZERO WASTE SEWING BACKGROUND

While the term "zero waste sewing" is relatively new within fashion design studies, first used in 2008, the practice of producing such garments in this manner is far older [55]. There are many examples across the world and throughout history of low and no waste garments, such as the kimono and sari. Zero waste fashion design, in its modern form, is an emerging area of teaching and research in fashion design programs. Though not a standard part of the curriculum at this point, a few art schools have begun offering specialized electives in the topic [49, 50]. While the current community of zero waste fashion designers is quite small, the community shares many of its insights through books, blogs, and downloadable patterns.

2.1 Conventional pattern cutting and sewing

By some estimates, cut and sew garment manufacturing, in which 2D panels are cut out of sheets of fabric and assembled into 3D garments, results in approximately 15% of the fabric being wasted [43]. Inefficiencies in pattern cutting and sewing arise from a divide between considerations of how the garment will look (i.e., its style) from how it is made. Typically the processes of designing the garment panels and laying them out to cut on the fabric, a process called *pattern cutting*, are distinct with layout considerations having relatively little influence on the garment's shape.

By integrating pattern cutting into the design process, zero waste fashion design bridges these often distinct processes. Noting the opportunity for pattern cutting to influence garment style by being considered earlier in the design process, zero waste fashion designer Timo Rissasen has written, "Pattern cutting in zero waste fashion design is a generative rather than reactive activity" [55]. There are a number of opportunities in considering the material constraints earlier in the process but relatively little digital support for doing so. It is worth noting that while a wide range of conventional sewing patterns are available online for purchase, there are relatively few examples of zero waste garments. For example, as of March 2024, the popular sewing pattern website The Fold Line [37] has only 13 zero waste patterns in their database of over 10k patterns.

2.2 Challenges in zero waste fashion design

While the constraint of utilizing all available material is strict, in practice there are many potential ways to achieve such an outcome. While there have been a few initial explorations of using simulation software for zero waste clothing design [44], overall the use of digital tools has been limited, with designers using tools, such as the 2D drawing program Adobe Illustrator and the 3D clothing design tool Clo3D, which are not specialized for zero waste design [63]. Many designers work on paper through a process of trial-and-error [17–19, 41]. There are several online resources for finding patterns, which can be adapted for different styles and body sizes. For example, recently several designers tried out variations of zero waste pants that wrap around the legs [17, 19, 41]. Adaptation of existing patterns provides an easier entry point to this highly constrained design space.

Based on our review of zero waste sewing books, blogs, and patterns, we found that the main challenges of zero waste design include navigating the complicated dependencies between panels, making edits within the context of the highly constrained pattern layout, and visualizing the resulting garment built upon often unconventional panel shapes. In order to address these challenges, we built WasteBanned to provide a tool for using linked edits to create garments that adhere to the zero waste constraints and for visualizing the material usage, 2D garment panels, and the resulting 3D garment simulation. We note also that while many zero waste patterns are truly zero waste in the sense that every part of the fabric goes into the garment, some patterns marked as zero waste are actually "minimal waste," accommodating small pieces of fabrics that are leftover [61]. Our tool supports this more flexible workflow by allowing some unused material to be set aside.

3 RELATED WORK

Our work builds upon prior work that explores the overlaps between textile design and material usage as well as a long history of papers at UIST that explore interfaces for constraint-based design (e.g., [5, 6, 22]). We first review related tools and techniques for textiles and fabrication more broadly and then discuss prior work in design for reuse, repair, and unmaking.

3.1 Textile tools

Craft-focused applications in fabrication have explored knitting [21, 25, 27, 42, 47], embroidery [68], smocking [16, 53], quilting [2, 8, 31, 32, 34, 36, 38], sewing soft objects [24, 46], and designing inflatables [58]. For garments, prior work has explored placing simulated cloth on virtual models [23] and creating realistic virtual clothing [14]. One of the key challenges in sewing real 3D objects, such as garments, is working across 2D panels and the corresponding 3D forms. Prior work has developed techniques for supporting garment editing in both 2D and 3D using correspondences between edges on the panels (i.e., seams) [3, 4, 62]. Recent tools have been developed for creating parameterized sewing patterns, allowing for custom resizing of linked elements [10, 30]. While most tools assume design in 2D before simulation in 3D, recent work has also explored how to go from 3D point clouds of garments to 2D sewing pattern panels [30]. Other tools have focused on simulating fabric behaviors in garments, such as fabric pattern alignment across seams [65], arranging pleats [35], and placing darts [13]. Commercial clothing design software, such as Clo3D [9], allows for the design and simulation of garments in different styles, sizes, and fabrics. Our work extends these garment design software tools by incorporating the unique constraints of zero waste design and focusing on the visualization of material usage.

3.2 Reducing waste through design

Recent work in computational design and fabrication has explored various ways to reduce and reuse resources. Koo et al. [29] support low-waste furniture design by suggesting design alternatives that utilize fewer materials. Scrappy [64] helps users use leftover materials as infill in 3D printed objects. EcoEDA [40] provides a database of parts and support for helping users recycle and reuse common electronic components. Prior work on visible mending has explored ways to increase the lifespan of textiles [26]. Others have explored the use of biodegradable materials, such as leaves for a heating pouch [59], leftover coffee grounds for 3D printing [56], and fallen branches for architectural design [67]. Roadkill [1] optimizes for efficiency in terms of assembly time through nested 2D panels with finger joints. Most similar to our work, InStitches [33] helps users repurpose fabric leftover between garment panels for sewing practice. There have also been broader conversations in the HCI community around reuse, salvage fabrication, and unmaking (e.g., [15, 25, 60]) as areas where design can advance sustainable making. Recent work has focused specifically on how to make textile applications of HCI more sustainable through the design, production, and use phases of these textile objects [45]. In this work we focus on reducing waste in garment sewing by making it easier for users to design zero and low waste garments.

4 SYSTEM OVERVIEW

We implemented WasteBanned as a web application that supports interactive pattern cutting and simulation with embedded zero waste constraints. The UI is structured according to the three main steps of pattern design: shaping 2D panels and laying out these panels on fabric (*Pattern Editing* view), sizing and arranging the panels on the body (*Pattern Alignment* view), and constructing the 3D garment (*3D Simulation* view). These three steps are shown

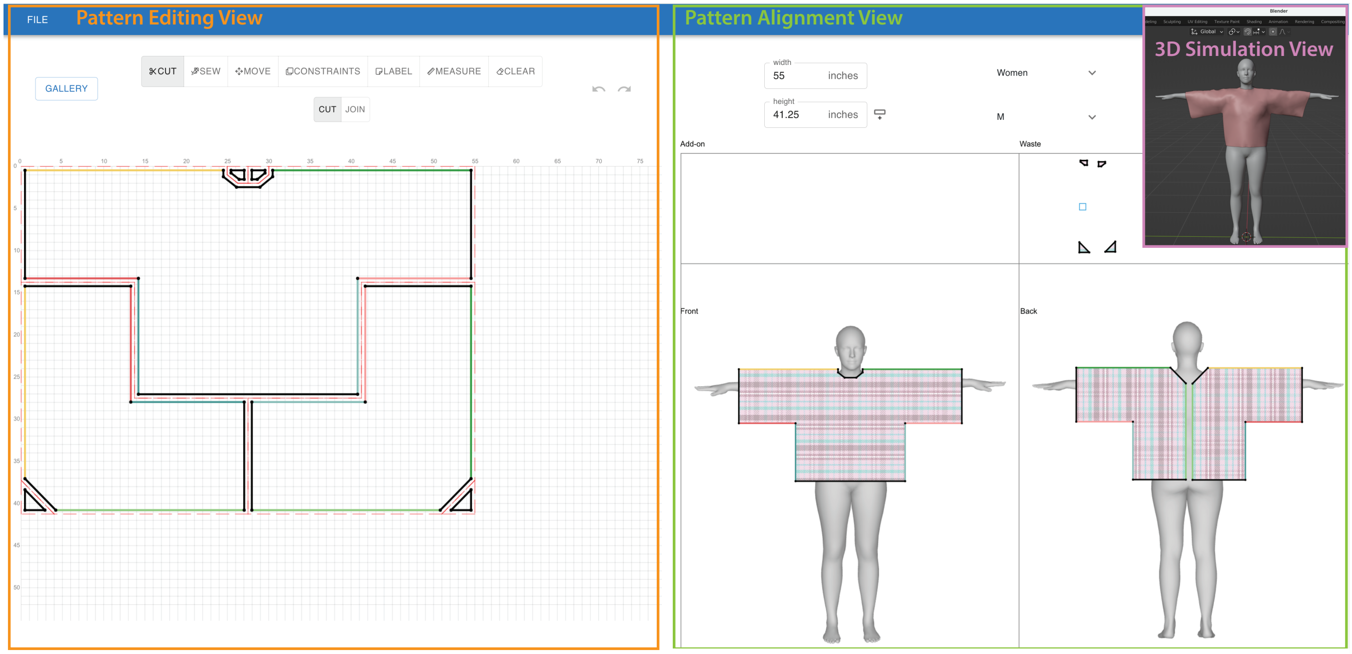

Figure 2: Users cut, adjust, and assign seam correspondences to the edges of the 2D panels in the *Pattern Editing* View. Users place the panels onto the model in the *Pattern Alignment* View. By clicking the"simulate" button, users can see the garment in the *3D Simulation* View in Blender.

simultaneously as part of the overall system goal of integrating awareness of design and material usage together and helping users navigate the strict design constraints of zero waste sewing. We will first provide an overview of each panel and then a walk-through of creating a skirt pattern.

4.1 Pattern Editing View

The *Pattern Editing* view is the main area where the user divides a sheet of fabric into 2D panels for the garment. Users are able to freely create, modify and adjust the panels within the strict zero design constraint framework by selecting among the cut, sew, and move menu options. Users can choose to create the pattern from the blank rectangle panel or adjust an existing pattern. We provide 8 default patterns [54, 66] pre-loaded into the tool, which users can access through the "gallery" button. All patterns are displayed on a grid, and we provide a measurement tool, which allows users to click on an edge to see its length.

4.1.1 Cut mode. In cut mode the user drags and draws lines that partition the rectangular fabric panel into polygonal panels. Cuts do not need to extend edge to edge, and slits are allowed for shaping (Fig. 5). In addition to placing cuts, users can also adjust existing cuts as they shape the panels. They can move individual vertices and edges or apply CAD-like constraints. These CAD operations include requiring that a set of lines be parallel, perpendicular, or equal length (please see Sec. 5.5 for more details about these constraints). In the context of sewing, these constraints are useful for creating garment panels that can easily be joined along edges at seams (i.e., panels with the same length will sew together smoothly). Although curved pieces are occasionally used in advanced zero waste designs, rectangles and triangles are the most common shapes so we only allow straight line cuts [55].

4.1.2 Sew mode. An important step in pattern design is labeling correspondences between edges of different panels that will be sewn together (e.g., the seam down the side that connects the front and back of a shirt). In sewing mode the user clicks on two edges to indicate this correspondence, which is shown by making the lines the same color. In order for two edges to be sewn into a smooth seem, they must be the same length. After sewing seams, the system automatically adjusts the edges to be the same length in order to meet this equal length constraint. This may lead to adjustments in the sizes of the neighboring panels so users may choose to measure the panels at this point or simulate the garment to ensure fit.

4.1.3 Move mode. Designing zero waste patterns is an iterative process, and users often have to make many edits to adjust the shape of each panel to achieve the desired fit and style. To adjust the size of a panel, the user can drag vertices to the desired location, and to erase edges, they can enter merge mode, which removes the cut and combines adjacent polygons. Any of these adjustments will result in any paired edges also being updated if one is moved. If the user does not wish to update the pair, they can remove the correspondence before dragging any vertices or edges. Any movement of vertices or edges still preserves the zero waste property of assigning each part of the fabric sheet to a different part of the garment.

4.1.4 Label mode. Label mode allows users to label panels to make it easier to keep up with where to place the panels later in the

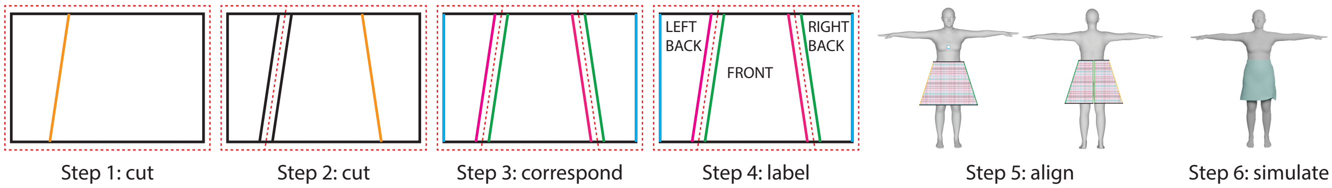

Figure 3: To make a skirt, the user starts with a rectangular panel of fabric and places cuts for each of the panels (steps 1-2). They add seam correspondences (blue, pink, and green lines) to indicate edges that will be sewn together and label the panels with respect to the body position (step 4). They then align the panels on the body (step 5) and simulate the garment (step 6).

design process. Because of the way panels are often rotated and arranged, keeping track of panel names can be useful. Common labels include "front," "back," "left sleeve," "right leg," etc.

4.2 Pattern Alignment View

The *Pattern Alignment* view allows users to place the garment panels roughly on the digital mannequin. This allows users to estimate the fit before simulating the garment. It includes four main areas where panels can be placed: the front of the body, the back of the body, add ons (e.g., pockets), and currently unused pieces. Users can select among 6 pre-loaded body models in a variety of sizes. We used SMPL [39] to generate this initial set of models across 6 randomly selected H&M men's and women's size measurements [20], but users can upload any body model in OBJ format for customization. One side of the fabric panels is colored in a default plaid pattern to help the user orient the fabrics properly with respect to the body. Add-on's, such as pockets, are not simulated but can be included in the pattern when downloaded. Ideally, all of the panels end up contributing to the end garment to create a fully zero waste design, but in some cases some fabric may go unused, at least temporarily. While every piece must be assigned one of the four areas within the Pattern Alignment view, we do allow users to assign pieces to the unused bin, which allows users to create low waste, rather than zero waste designs, if needed.

4.3 3D Simulation View

The *3D Simulation* view allows the user to preview the shape of the garment on a human model. Our simulation includes some default cloth simulation parameters, which users can customize.

If users are happy with the garment's appearance, they can proceed with downloading the pattern cutting layout from the Pattern Editing view. If they find that the fit or style needs adjustment, they can continue to iterate on the pattern.

4.4 Example skirt UI walk-through

To illustrate how a user would create a zero waste garment in the three views in the UI, we will walk through an example of creating a simple zero waste skirt.

4.4.1 Cut mode. To create a skirt, the user starts with a panel of fabric the dimensions of the available material, in this case 56 x 41.25 inches (Fig. 3). Then, they add the first edge-to-edge cut for one of the back panels. A yellow line appears as they drag the mouse, indicating the cut (Fig. 3, step 1). After they release the mouse, the seam allowance (i.e., the region of fabric consumed by sewing the seam) is automatically added. This original cut they placed becomes a red dashed line, and the panel edges, which account for the seam allowances, become black lines. They then create a second cut for the other back panel (Fig. 3, step 2).

4.4.2 Sew mode. The user marks correspondences between seam edges using "sew" mode by clicking pairs of edges that will be sewn together in the skirt. We see the corresponding pairs of edges denoted in the same colors in Fig. 3, step 3. The middle panel is the skirt front, and the two smaller panels on the sides are the skirt back panels upside down with the waistline edge on the bottom.

4.4.3 Label mode. The user adds labels to each of the panels (Fig. 3, step 4). This helps them remember how to orient the panels, which is particularly important for more complicated patterns.

4.4.4 Panel alignment. The user drags the panels into their rough position on the body, placing the top edge of the skirt front and back panels along the waist of the digital model. They can see that the corresponding edges with the same colors marked as sewn edges are now aligned.

4.4.5 Simulation. The user can then click "simulate" and view the garment in Blender. In this case, the fit looks good, but if there were any issues with the fit, they could simply return to the Pattern Editing or Pattern Alignment views and make adjustments to the widths of the panels or the angle of skirt edges.

5 IMPLEMENTATION

One of the primary challenges of working within a zero waste paradigm is keeping up with the strict constraints it imposes, namely using all or nearly all of the material, linked editing, and performing edits that affect neighboring panels in the layout. The three basic operations of creating a zero waste sewing pattern are: ***cut***, ***merge***, and ***sew***. We support these operations by splitting and merging polygons and encoding constraints on the edges of the polygons. In this section, we describe how we represent and handle these constraints and implemented them in the UI.

5.1 Sewing pattern representation

WasteBanned is implemented as a React web app that communicates with FreeCAD [12] for constraint solving and Blender [11] for simulation. In the UI users operate on polygonal panels. New panels are created by splitting or merging existing polygons. We use a half-edge data structure (Fig. 4), a common data structure for representing meshes:

- **Vertex**: A 2D point, $u = (x, y)$ corresponding to a location on the 2D garment panel's outer boundary.
- **Half-edge**: An edge $e = (u, v)$ that connects two vertices, u and v. Its direction is defined by the vector $\vec{uv}$, and it is doubly linked.
- **Face (panel)**: A list of half edges, forming closed polygons. We chose a clockwise orientation for the edges.

As the user places cuts to design the garment, the half-edge data structure gets updated to preserve the orientation of the edges around the faces (Fig. 4).

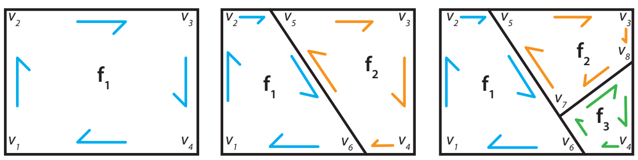

Figure 4: We use a half-edge data structure to represent the fabric panels. (a) Initially we choose to set the orientation of the half-edges (blue arrows) clockwise. (b) To split this panel, we add two vertices v_5 and v_6, which split edge e_{23} and edge e_{14}. The orientation for this new face f_2 is also clockwise. (c) We can continue to split in this way to add face f_3.

5.2 Editable edges vs. reference edges

The UI keeps track of both the edges drawn by the user and those corresponding to the size and shape of the resulting garment panels. ***Reference edges*** (shown in dashed red lines) form the original polygon panels the user cut (Fig., 3, steps 2-4). ***Editable edges*** (shown in solid lines) take into account the seam allowances (i.e., the regions of fabric that are consumed by the seams) of the garment panel (Fig., 3, steps 2-4). We set the default seam allowance to be 0.5in. Every editable edge is created by moving its reference edge counterpart toward its normal direction by the default offset. When users make a cut and form two edges, the seam allowances are offset automatically, and the corresponding editable edges are created.

5.3 Panel cuts and merges

We define a cut as a line segment (u, v), and we support three common operations in cutting a zero waste pattern panel:

- **Edge-to-edge cut**: The start point u and end point v are on two different edges belonging to the same face.
- **Slit**: For a slit, either the start point u or the end point v is on the edge, and the other cut point is within the face.
- **Break point**: The break point splits an edge at a point.

Cuts cannot extend across multiple faces (i.e., no intersections in which the edges have length > 0 on both sides of the intersection point). As the designer makes changes, they sometimes need to merge existing edges to undo a cut or join adjacent panels. In most cases, simply reversing the cut operations allows us to merge panels.

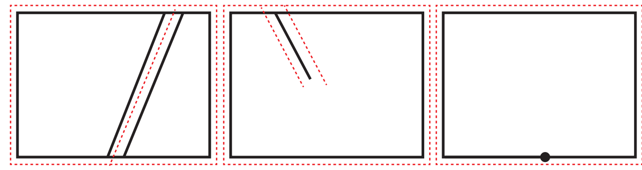

Figure 5: (a) An edge-to-edge cut splits an existing panel. (b) A slit cut makes a cut in a panel that does not split the panel into multiple pieces. (c) A break point splits an edge.

5.4 Constraint solving for linked edits

To achieve linked edits for the whole pattern, we translate the linked edits into linear constraints and solve using FreeCAD [12] (please see Sec. 5.5 for more detail about the constraints). We use WebSocket to connect the UI and FreeCAD with bidirectional communication. Whenever users make edits to the pattern, the UI sends the edge data and drag-move data along with the constraint data to FreeCAD. FreeCAD receives the data and recomputes the panel shapes given all of the constraints so that the selected vertex or edge is moved to the desired location and the recomputed full pattern still meets the constraints. After recomputing, FreeCAD sends the updated edge data to the UI and updates the edge positions accordingly.

5.5 Constraints

We leverage FreeCAD [12], an open source parametric design tool, to perform geometric constraint solving. FreeCAD incorporates many standard CAD operations, such as extrude, slice, etc., but we only utilize a subset of the operations relevant to designing 2D fabric panels. Specifically, we use the built-in 2D constraints "horizontal," "vertical," "perpendicular," "coincident," "parallel," and "equal" in our tool. We expose these lower level constraints in the UI so that users who are familiar with CAD systems can apply these constraints directly. However, we also build on top of these low level constraints to encode the higher level zero-waste specific constraints. We put constraints into two categories: **zero waste**, which are automatically induced by zero-waste criteria, and **user added**, which are voluntarily added by the users in the UI and typically correspond to lower level CAD operations, such as making an edge horizontal or two edges parallel.

5.5.1 Zero waste constraints. Zero waste constraints arise from the specific needs of designing zero waste clothing. These include constraints related to ensuring that the lengths of edges that will be sewn together remain the same length and that edits to one panel properly update neighboring panels in the layout. The user begins with a rectangle of fabric, and each subsequent cut preserves this "use everything" property. Applying a "sew" operation to any pair of edges imposes the equal length constraint on these two edges. As the user makes cuts, the initial constraints on edges that do not change (e.g., $e_1 = e_3$ and $e_2 = e_4$ in Fig. 6, left) remain in place as the user makes further cuts. For any cut $c_i = (p, q)$, if point p falls on the edge $e_i = (s, t)$, the edge splits into two shorter edges $e_i = (s, p)$ and $e_j = (p, t)$. We add "coincident" and "parallel" constraints on the two edges (e_i, e_j). Any existing "coincident" or "parallel" constraints (e_i, e_n) starting with edge e_i are added to

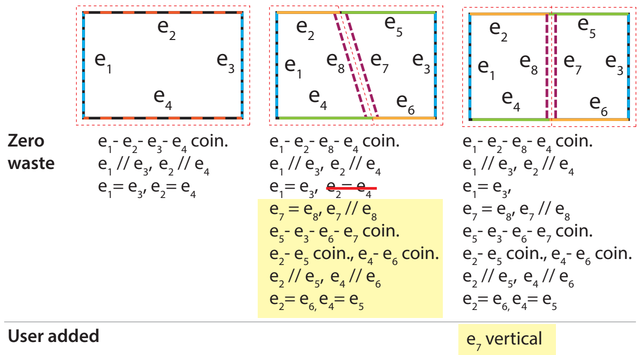

Figure 6: The initial rectangle has implicit equal constraints for the parallel pairs of edges (left, dashed lines). Once the user makes a cut, the tool automatically updates the existing zero waste constraints and adds an equal constraint for the panel edges on each side of the cut line to allow for the seam allowances (purple dashed lines, center). If the user decides to sew the two panels along the top and bottom edges (yellow and green solid lines, center), then the zero waste constraints get updated (yellow highlight, center). The user can also add CAD-like constraints, such as making e_7 vertical (right).

(e_j, e_n). When merging the cut c_i, we remove the constraints added for the cut. The two edges $e_i = (s, p)$ and $e_j = (p, t)$ are merged into one longer edge $e_i = (s, t)$. We then remove the "coincident" and "parallel" constraints added for (e_i, e_j). Any existing "coincident" or "parallel" constraints on (e_j, e_n) starting with edge j are applied to (e_i, e_n) (e.g., Fig. 6, center).

5.5.2 User added constraints. Users can add "horizontal," "vertical," "perpendicular," "parallel," and "equal" constraints manually in order to update the design using common CAD operations. The user added constraints are also handled by FreeCAD. In Fig. 6, in the final stage, the user applies a vertical constraint, and the corresponding edges snap into position vertically.

5.5.3 Redundant constraints handling. Handling redundant constraints is a known limitation of FreeCAD [7, 51, 52]. We detect redundant constraints on the front end to avoid passing along these issues to the solver. For example, in Fig. 6a the equal constraints $e_1 = e_3$ and $e_2 = e_4$ are redundant given the coincident and parallel constraints for these edges. We detect redundant constraints by keeping track of embedded constraint groups for "parallel" and "equal" because of transitivity (e.g., if $a \parallel b$, $b \parallel c$, then $a \parallel c$). A constraint group includes elements which share the same constraint with every other element in the group. We generate the constraint groups for both zero waste and user added constraints and prevent these redundant constraints from being sent to the solver.

5.6 Clothing simulation

We leverage Blender [11] for 3D simulation. WasteBanned uses cloth parameters that Blender recommends for simulating clothing weight cotton using its mass-spring cloth model. The cloth behavior could be tuned for other materials by adjusting the set of parameters (vertices, mass, viscosity, stiffness, etc.).

5.6.1 Coordinate system transformation. To transform the polygon panel data from the UI to a mesh for simulation, we perform a two-step coordinate system transformation:

(1) The browser uses the top-left corner of the viewport as its origin. We transform the vertices of the polygon panels from the browser viewport origin to the standing point of the model in the front view or back view.
(2) Blender uses a right-angled Cartesian coordinate system: the Z axis pointing upwards; the X axis pointing right; the Y axis is pointing front. The model is positioned at world coordinate $(x, y, z) = (0, 0, 0)$ standing on the ground facing front. The panels in the front of the model are on the plane $y = 2$ and those in the back of the model are on the plane $y = -2$. A point on the panel in the UI (x_{UI}, y_{UI}) is mapped to (x, z) in Blender coordinates.

5.6.2 Triangular meshing. To turn the 2D panel shapes into meshes, we first evenly add Steiner points on the boundary edges of each panel (Fig. 7). Then, we utilize Triangle [57] to generate a triangular mesh for each panel based on these boundary points. A pair of seam correspondences must have the same length and thus have an equal number of Steiner points. The built-in Blender cloth simulation module adds "sewing thread" between the points along the edges to turn polygon meshes to a 3D sewn form. As the simulation runs, the meshes are pulled towards each other by the sewing threads and are wrapped around the model. We use Blender's default cloth simulation parameters (Appendix A).

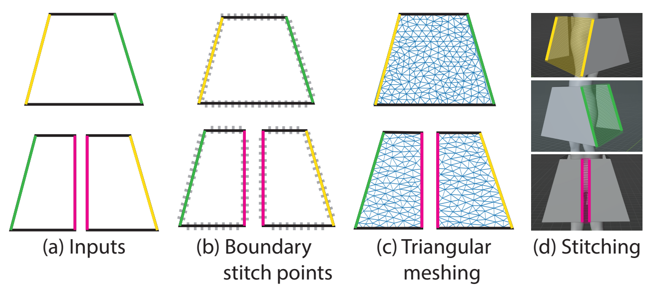

Figure 7: We automatically add Steiner points around the boundary of each panel to create the mesh. We then "stitch" the sides of corresponding panels to simulate it.

6 REPRESENTING ZERO WASTE PATTERNS

We collected a set of 8 patterns from a zero waste sewing pattern book [54] and online resources [66] and used WasteBanned to adapt the patterns in a default size of H&M women's medium[20]. For patterns with curves, we used smaller line segments to approximate curved necklines, pockets, and other small styling panels. The T-shirt and open front shirt ended up with small amounts of waste after approximating the curves. Patterns with more pieces, such as the hoodie, open front shirt, and shorts tended to also have more seam correspondences and constraints (Table 1).

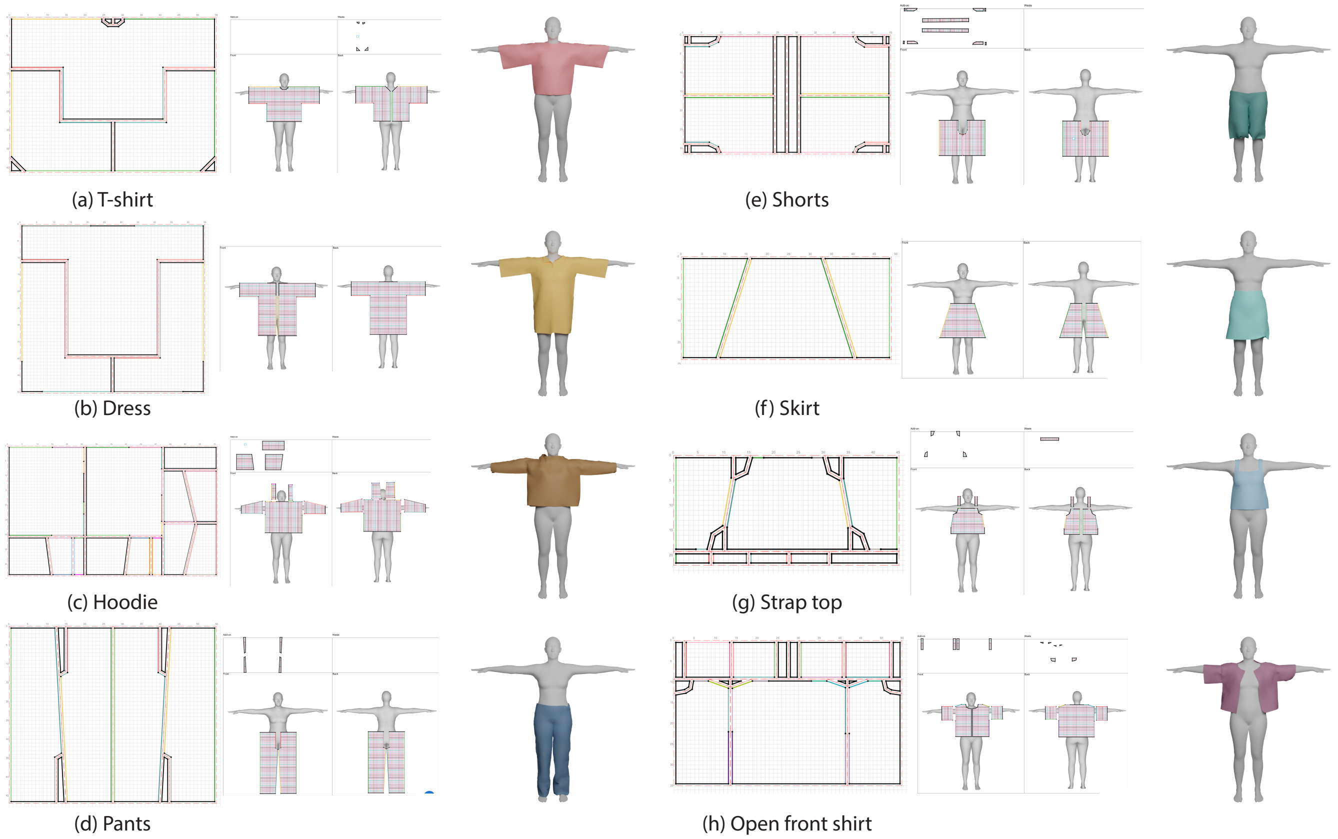

Figure 8: We used WasteBanned to simulate 8 adaptations of existing zero waste sewing patterns [54, 66] with a range of styles. For designs with curved edges, such as necklines, we approximated the panel edges using straight line segments (a, d, e, g, and h). Colored edges indicate seam correspondences.

Pattern	Num Panels	Sim Panels	Num Edges	Num Seams	Num Cons
T-shirt	7	3	44	6	100
Open shirt	17	7	82	14	183
Strap top	12	7	64	9	136
Hoodie	13	10	63	19	154
Pants	8	4	40	8	90
Shorts	14	4	72	10	160
Skirt	3	3	12	3	28
Dress	3	3	26	7	62

Table 1: We used WasteBanned to simulate 8 zero waste sewing patterns. Some patterns have elements (e.g., pockets) that are not simulated. Patterns with more pieces, such as the hoodie and open shirt, tended to have more seam correspondences and constraints, indicating greater complexity.

7 USER EVALUATION

Our formative work indicated that adapting the size and style of existing patterns is a common way for people to learn zero waste design so our study tasks focused on adaptation. We focused on two common tasks in the zero waste clothing design process: adjusting a garment's fit and updating its style. Our goal was to determine if WasteBanned could successfully support these tasks for users with a range of experience levels in sewing and design more broadly.

7.1 Participants

We recruited 6 participants from a local university for our user study. Participants were all new to zero waste garment design. Four participants (P1, P2, P3, P6) were familiar with SVG drawing tools (e.g., Adobe Illustrator, inkScape), and three had used CAD software (P2, P3, P6). Three participants (P1, P2, P3) had prior garment design experience, and four participants had sewing experience (P1, P2, P3, P6). P1, the most experienced participant, studied fashion design for 4 years as an undergraduate.

7.2 Study protocol

Our user evaluation comprised 90-minute sessions. In the first 15 minutes, we provided a video introduction of WasteBanned and a live demo of the tool. Next, participants were instructed to complete two main design tasks: resizing (15 minutes) and restyling (45 minutes) an existing garment from among the 8 designs preloaded into the tool. For the resizing task, participants were asked to

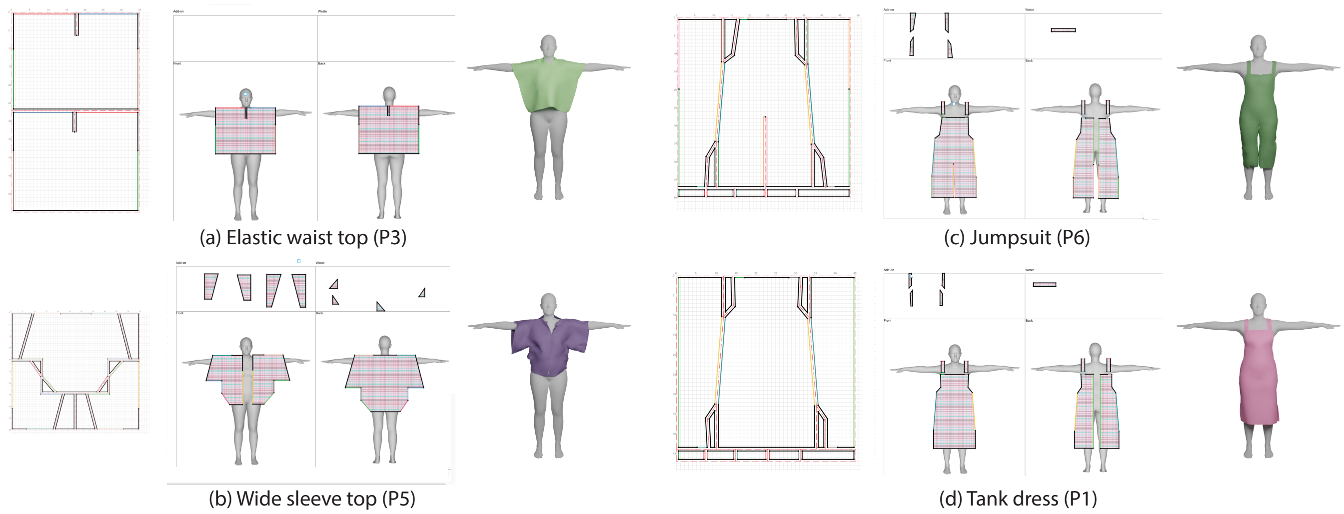

Figure 9: For the restyling task, P3 made an elastic waist top (a), P5 adjusted the style of the sleeves in the t-shirt to make a wide sleeve top (b), P6 made a jumpsuit by adding straps to the pants pattern (c), and P1 made a tank dress from the pants pattern (d).

resize one or two patterns from the default size to another specified model size. For the restyling task, participants were instructed to add or adjust an existing style for a pattern. Each participant was free to choose any of the available patterns for each task. After completing the two tasks, participants were interviewed about their experience with the tool and zero waste design more broadly.

7.3 User study results

The resizing task took participants 10-15 minutes, and the restyling task took 35-45 minutes. For the resizing task, all participants were able to adjust the garment to fit for the intended model while keeping the garment similar in style to the original. For restyling, 5 out of 6 participants managed to restyle an existing pattern to remain low waste and fit the model. P4, the participant who was unable to achieve their desired design, attempted the particularly difficult process of combining the pants pattern with the strap top pattern to turn it into a jumpsuit. They were not able to get the size of the bottom of the top to fit with the waist measurement across the pants with the available fabric. However, P1 and P6 attempted a similar type of restyled design by adapting the pants pattern into a jumper dress or jumpsuit and were successful (Fig. 9). On the scale of 1 (very challenging) - 7 (very easy), participants rated resizing to be relatively easy (median=6), and restyling to be more difficult (median=2.5). Participants indicated that they found the tool fun to use (median = 6/7) and that they would be likely to use it again for zero waste design in the future (median = 6/7).

7.3.1 Understanding zero waste constraints. Participants, even those without fashion design experience, indicated that they were able to understand the available constraints and how they affected the resulting garment design. Participants said that they particularly appreciated the linked edits for making sure their designs remained zero waste throughout. P3 compared this domain-specific editing support to their experience using more general purpose vector editing tools for fashion design. Comparing WasteBanned to Adobe Illustrator, they said, "This tool is smarter because it is very convenient to move one edge and the whole pattern gets updated according to the constraints. It saves a lot of trouble." Participants, all of whom were unfamiliar with zero waste garment design coming into the study, indicated that the tool helped them learn about the zero waste constraints (median = 5.5/7). They also indicated it made the task of designing zero waste garments easier than using a tool without these embedded constraints (median = 6/7).

7.3.2 Supporting exploration of design variations. For the more open-ended task of restyling a garment, participants chose a range of different adjustments. P1 turned the strap top into a tank dress, P3 created an elastic waist dress, P5 adapted the t-shirt into a wide sleeve top, and P2, P4, and P6 created jumpsuits or jumper dresses (Fig. 9). These adjustments involved simplifying an existing pattern (Fig. 9a), extending an existing pattern, such as adding straps to the bottom of the pants panel (Fig. 9b, d) to make jumpsuit, and subdividing existing panels to adjust the shaping of a panel (Fig. 9c).

P1, who studied fashion design in college, quickly came up with an original zero-waste design during the session (Fig. 10). This design uses all three categories of cuts WasteBanned supports: edge-to-edge cuts to separate the front and back panel, slit cuts for the neckline, and breakpoints for sleeves. This experienced designer noticed that many of the existing zero waste patterns lacked much shaping. They wanted to challenge themselves to create a top that would be more fitted. While they thought that they may need elastic for this, they discovered that they could actually create a more fitted zero waste design by cutting angled sleeves from the rectangle, leading to a smaller waist for the garment and a flared shirt bottom.

7.3.3 Supporting diverse and iterative workflows. Participants explored different orders for going through the process of adjusting designs. P2 first sewed the panels and then adjusted the linked edges by moving them. P3 liked to have the edges equal lengths first before assigning sewing edges. P2 discovered they sewed the

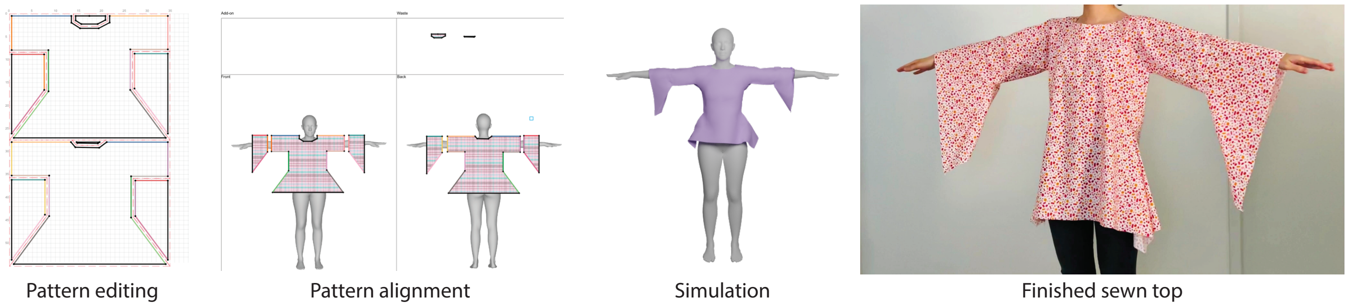

Figure 10: P1 created a nearly zero waste bell sleeve tunic using WasteBanned. They first split the rectangle in half vertically to create a back and front panel, designed the shape of the tunic and sleeves, and then added the seam correspondences (left). They aligned the panels on the body model, which happened to be a little larger than their own body. The only leftover materials are the small regions in the front and back neck area. Next, they simulated their garment, downloaded and printed their pattern, and arranged the panels on the fabric following the layout diagram in the UI. Finally, they sewed it in pink floral fabric (right).

wrong seam correspondences after checking the simulation, resulting in the front and back panels being turned the wrong way with respect to each other. They came back to the UI, removed the incorrect correspondences, and added the correct ones. P2 said that this experience helped them better understand the correspondences and the challenges involved in navigating the constraints. P4 described WasteBanned as a "computer version of paper miniature prototyping." They found that this matched existing prototyping practices in zero waste clothing design, saying, "There are some folks that like using paper miniatures to think through complicated patterns, and this was a fun computer version of that with Blender simulations." P6 suggested a symmetry mode that would allow them to edit half of a garment and have those edits propagate to the other half.

7.3.4 Learning about zero waste design. Participants also shared their broader thoughts on zero-waste design after working with the tool. P2 said that restyling a garment was almost like "designing something new" because of the difficulty of the constraints but that the tool helped them navigate these issues. Both P3 and P4 came to the conclusion that zero-waste design is more challenging for more fitted styles compared to traditional clothing design. P4 shared:

> Zero waste can be very simple or very hard depending on what you want out of a garment! There are lots of fun billowy zero waste patterns you can use, but the moment you want something a little more form fitting, it can get difficult.

This observation is in line with what we see in existing zero waste sewing patterns; most zero waste garments are very loose compared to standard garments. However, as we see in the garment P1 created (Fig. 10), WasteBanned can support users in creating garments that have a more fitted shape.

All participants agreed that the tool helped them to learn about zero-waste design. P1 especially liked the gallery of existing designs for getting started, saying, "The gallery templates are very helpful starting points for a design novice like me. It's nice to have the garment pieces laid out and constraints defined so I can make adjustments and understand zero-waste design implementation better with the tool." Participants indicated that support for linked edits was particularly useful. P4 said that linked edits are the most challenging part of zero-waste design, and the tool helped them navigate working with them:

> Zero-waste clothing design is a really fun problem. I did appreciate that this tool really forced me not to cheat and have little pieces randomly cut off…I appreciate how this tool auto-adjusts the proportions of the other pieces in the pattern when you change a seam. That's actually the biggest headache for me when I think about zero waste patterns. This tool took that headache away.

Participants said that WasteBanned raised their awareness of fabric waste in clothing design by drawing their attention to minimizing fabric usage in the design process.

8 DISCUSSION

Our initial exploration of software to support zero waste fashion design contributes to ongoing discussions around sustainable design in many different domains.

8.1 Generalization to non-sewing domains

Zero waste sewing is an extreme example of considering materials earlier in the fabrication process, but this approach to designing tools certainly applies to other domains. Many of the ideas we have presented in this paper around connecting CAD and CAM and balancing the design and layout of panels that comprise 3D manufactured forms are relevant to other forms of manufacturing beyond textiles, such as sheet metal and glass cutting. Other objects made of 2D sheets of material, such as sheet metal and wood, require similar consideration of design and layout when it comes to anticipating waste.

8.2 Improving sustainability in garment design

From producing the raw materials to assembling and transporting the garments, there are many points in the clothing production process at which energy and materials are wasted. The fashion industry has been exploring many different paths toward reaching a more sustainable future; strategies, such as circular design, which aims to recycle as many materials as possible, the development of more environmentally friendly fibers, such as Lycocell, and garments knitted from a single strand of yarn, are all part of this shared goal to reduce waste. Improving sustainability in the production of garments requires taking a variety of steps, one of which is rethinking the design and layout of sewn garments, which this paper addresses. We could also imagine different ways to interpret the challenge of zero waste, such as incorporating fabric folding or origami. We hope that by making it easier to design zero waste garments, we are allowing more designers to work within these constraints and consider material usage earlier in the design process.

8.3 Viewing constraints as an opportunity

Zero waste fashion design imposes relatively strict constraints. While these constraints can be burdensome, a different framing casts them as inspiration to innovate on new styles of clothing. Rissanen writes: "Zero waste fashion design addresses inefficiency in fabric use by reframing fabric waste as an opportunity to explore the magic of fashion; just like all fashion, zero waste fashion celebrates experimentation and the discovery of new forms" [55]. This approach of viewing constraints as inspiration rather than a limitation speaks more broadly to how constraints are presented to the user and how example outputs are shown and explained. In this highly constrained, relatively under-explored domain, we chose to provide a small set of examples of existing garments for inspiration. An interesting area of future work is evaluating the trade-offs between encouraging editing versus authoring from scratch.

8.4 Limitations & Future work

While we encode the constraints necessary for users to create and edit zero waste designs from sheets of fabric, there are additional types of constraints that could be useful as well. For example, while the simulation of the garment on the body model provides some feedback about fit, the tool currently does not provide feedback on fit in the other two views, nor are there explicit constraints based on body measurements. The CAD constraint solver we currently use cannot handle inequality constraints, which would be needed to match seams with different lengths. A promising area of future work would be supporting these additional edits by building a custom solver.

There are some cases in which certain types of edits are infeasible. For example, widening a skirt that is currently an XS to an XL may not be possible without additional fabric. While the user can discover this through the editing process, in the future it would be useful to consider how to provide better feedback about what types of resizing or restyling edits may be possible or the minimum amount of fabric needed to achieve a garment at a certain size.

While this initial version of our tool uses Blender for simulation, another tool that supports cloth simulation could be used in the future, potentially in the browser alongside the other UI views. Enhancing simulation fidelity, such as by using higher quality meshes and cloth simulation tools, could also improve the quality of the outputs and the experience of designing with WasteBanned. Supporting editing of the 3D garment and propagating those edits back to 2D could be added using techniques explored in prior work for editing standard (non-zero waste) sewing patterns (e.g., [62]) and would be a useful extension.

Our tool currently supports only straight cuts, which cover a wide range of different garments, but in the future adding curved cuts while adhering to these zero waste constraints could further expand the design possibilities. Matching equal length seams that are straight lines is straightforward; however, with curved seams there are many possible seams with equivalent length but different curvature. An interesting area of future work is helping users explore a set of equivalent length seam curves that would produce well-fitting and stylish garments. Future work could also explore how to adapt existing conventional patterns to zero waste designs with similar fit and style properties. Our current tool is designed largely around creating a single garment at once within a sheet of fabric. Future work might consider designing multiple garments together to allow for more layout possibilities.

9 CONCLUSION

In this paper we introduced a tool for editing zero waste sewing patterns through combining CAM and CAD operations. By treating material usage as a critical part of the garment design process, we hope to encourage further experimentation of zero waste garment design. We believe that this is an important piece of the larger puzzle of improving sustainability in design through prioritizing material usage constraints in computational design tools.

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A BLENDER PARAMETERS

We use a set of default cloth parameters in Blender for the garments we simulate. Users can adjust these parameters if needed to better match their intended fabrics. The default parameters are the following:

- Vertex mass: 0.3kg
- Air viscosity: 1.0
- Stiffness tension: 15
- Damping tension: 5

B USER EVALUATION QUESTIONS

Ahead of the user evaluation, we asked participants the following questions about their experience with garment design:

(1) Which of the following apply to you?
  - I have sewed a garment from an existing pattern.
  - I have designed a garment pattern myself.
  - I have not sewn before, but I am familiar with how garments are constructed.
  - I have made alterations to an existing garment (e.g., shortened sleeves, mending, etc.)

(2) Which of the following apply to you?
  - I am a self-taught sewist.
  - I have watched how-to-sew videos online.
  - I have taken sewing classes.
  - I have taken fashion design classes.
  - I own a sewing machine or have regular access to one.

(3) Which of the following apply to you?
  - I have used CAD software.
  - I have watched how-to-sew videos online.
  - I have used Blender, Maya, or another similar modeling/simulation tool.

(4) If you have sewed garments before, how would you rate your sewing experience level?
  - Beginner
  - Advanced beginner
  - Intermediate
  - Advanced
  - Professional

(5) If you have sewing experience, please briefly describe something you have made.

(6) If you have garment design experience, please briefly describe that here.

After our user evaluation, we asked participants the following questions about their experience using WasteBanned:

(1) Before this study how aware were you of zero waste clothing design?
(2) If you have previously designed garments, in what ways is designing zero waste garments similar and different?
(3) How likely are you to design and/or sew zero waste garments in the future?
(4) If you were to design zero waste garments in the future, how likely would you be to use this tool?